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Analysing uncertainties for CCS: from historical analogues to future deployment pathways in the UK

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Abstract

Whilst carbon capture and storage (CCS) technologies are now in the demonstration phase, they are still characterised by a range of technical, economic, policy, social and legal uncertainties. This paper presents the results of an interdisciplinary research project funded by the UK Energy Research Centre (UKERC). The aim of the project was to analyse the main uncertainties facing potential investors in CCS and policy makers wishing to support these technologies through demonstration to commercial deployment. The paper presents a framework for the analysis of these uncertainties, and applies this framework to nine analogue case studies of CCS. These case studies have focused on historical developments in technologies and/or policy frameworks where one or more of these uncertainties has been prominent – and have, in most cases, been partly resolved. The paper also shows applies the insights from these historical case studies to develop three potential pathways for CCS deployment in the UK over the period to 2030. Finally, the paper concludes with some implications for CCS policies and strategies.

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Keywords: Carbon capture and storage; uncertainty, innovation; policy

1. Introduction

Carbon capture and storage (CCS) technologies are often highlighted as a crucial component of future low carbon energy systems. However, they are still being developed and demonstrated. It is therefore unclear when these technologies will be technically proven at full scale, and whether their costs will be competitive with other low carbon options. For their supporters, CCS technologies offer a crucial way to

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square the continued use of fossil fuels with climate change mitigation. According to the International Energy Agency (IEA) World Energy Outlook in 2011, fossil fuels will continue to supply the majority of the world's energy to 2035, even if climate change mitigation is taken very seriously [1]. The IEA '450 scenario' considers a global energy system trajectory that has a significant chance of limiting average temperature increases to 2°C. Under this scenario, CCS would be fitted to 32% of the world's coal fired power plant capacity (410GW out of 1270GW) by 2035, and 10% of global gas fired capacity (210GW out of 2110GW) by the same date. CCS technologies would therefore account for 22% of the reduction in CO2 emissions by 2035 when compared to the IEA's alternative 'new policies scenario' in which global greenhouse gas emissions would continue to rise.

However, whilst many governments and companies are now funding and developing CCS technologies, there is a long way to go before we know whether such a role for CCS will be technically and economically feasible. Pilot scale capture plants are in operation in several countries, CO_2 is routinely transported across large distances in the United States, and CO_2 is being injected successfully at a number of storage sites. But full-scale CCS plants are thin on the ground [2]. Demonstrations so far focus on gas processing, synthetic fuels and fertiliser production – applications that are less technically demanding and more economically attractive than CCS in the power sector. According to the IEA, 'incorporating CCS into a power plant increases the levelised cost of the electricity produced by between 39% and 64%, depending on the technology and fuel source' [1, p378]. This increase is expected for two main reasons. First, the incremental capital costs of adding CCS to a fossil fuel power plant are substantial. Second, the energy penalty of including carbon capture in a power plant is significant.

Given these economically unattractive attributes, it is not surprising that there are no full scale CCS demonstrations in operation at coal- or gas-fired power plants. The first two are currently under construction in the United States and Canada, underpinned by government financial support. Plans for a number of other CCS power plants have recently been cancelled, including the Longannet plant in Scotland and the Ja□nschwalde plant in Germany. Whilst economic and financial factors were significant in the collapse of Longannet, the cancellation of Ja□nschwalde followed public protests against the planned use of onshore storage. The Global CCS Institute emphasises the particular importance of economic and policy barriers to such demonstration projects in a recent survey report [2].

The important role that CCS technologies could play has been recognised in recent UK policy debates. A commitment to government funding for full-scale demonstrations was made as long ago as 2007. Since then, progress has been slow. The original competition to build a demonstration project has not led to a firm agreement with project developers, and ended with the Longannet cancellation in Autumn 2011. In April 2012, a renewed policy push was made with the launch of the 'CCS Commercialisation Programme', and a CCS roadmap [3]. The government confirmed that £1billion of capital funding will be available for one or more demonstration projects, supplemented by long term contracts from an ongoing reform of the UK electricity market, and funds from the European Union's 'NER300' process.

Against this background, this paper summarises the findings of the two-year UKERC research project: *Carbon capture and storage: realising the potential?* [4]. The aim of the project was to conduct an independent, inter-disciplinary assessment of the technical, economic, financial and social uncertainties facing CCS, and to analyse the potential role CCS could play in the UK power sector between now and 2030. The remainder of the paper is structured as follows. Section 2 explains how the main uncertainties for CCS were identified, and how they can be assessed. Section 3 summarises the nine case studies that were used to explore these uncertainties, each of which focuses on a technology that is partly analogous to CCS. Based on the insights from the case study analysis, section 4 develops a number of potential CCS pathways for the UK to 2030. It also suggests a number of important branching points, where decisions could make a significant difference to the contribution of CCS plants to the future UK electricity mix. Section 5 concludes and sets out some important implications for policy and for other decision makers.

2. Analysing the key uncertainties for CCS technologies

The identification of key uncertainties for CCS technologies was an iterative process. An initial list of uncertainties across a range of technical, political, financial, legal and social aspects was drafted by the project team. The research process drew on the inter-disciplinary expertise on CCS and innovation within the research team, which includes geology, engineering, legal and financial and innovation studies. The draft list of uncertainties was further refined and tested in an iterative process with several steps. In line with contemporary technology assessment practice [5, 6], this process included consultation with the project's steering group, which included a range of experts from industry, policy and academia.

A social science literature review was undertaken in June 2010 to establish what is known about CCS uncertainties, as well as more fundamental insights about how to conceptualise and understand them [7]. We found that existing social science CCS publications tend to focus on a particular uncertainty such as public acceptance [8] or costs [9]. They do not tend to analyse CCS uncertainties across the board and their interactions over time. Where there was little social science research, for example on system integration, general innovation studies and policy literature were used. To further focus and ground the framework in an understanding of how new technologies are assessed in practice, 14 interviews with technology stakeholder representatives from the public and private sectors were conducted. The interviews were further complemented with a review of technology assessment documents.

The final list of seven key uncertainties for CCS innovation is presented in Table 1. They are elaborated in more detail in Markusson, Kern et al. [7]. As shown in the Table, qualitative and quantitative indicators were identified so that uncertainties could be assessed with more precision.

3. Historical analogues for CCS

Faced with the inherent uncertainties about the future of a new technology, it is common to draw on our experience of previous technologies that are analogous in some way. This happens both informally in discussions as well as through formalized comparisons in the development of designs, policies and strategies. A few previous studies have sought to use historical analogues to assess the potential future development of CCS technologies. Studies of CCS learning rates have tried to quantify the rate of learning experienced by mature technologies such as flue gas desulphurisation (FGD). They use this evidence to argue that CCS might develop similarly, with costs falling as CCS technologies are progressively deployed [9, 10]. There is also some qualitative research that compares CCS with other technologies, which is useful for exploring a wider range of innovation processes than can be compressed into a learning rate. This paper adds to this second tradition of qualitative research. In comparison with previous studies such as that by Chalmers et al [11], the paper includes a more in-depth analysis of a wider range of analogue case studies.

The historical analogues included in this study were chosen to be similar to CCS with respect to one of the seven uncertainties outlined in section 2. It is important to note that any analogue is necessarily different in some ways and can only ever be partial. This means that learning from analogues is never perfect. To make sure that the analogues were well chosen, a long list was first drafted, drawing on existing literature, stakeholder interviews and the inter-disciplinary research team. The draft list was further developed through a stakeholder workshop that included attendees from industry, government and academia. The workshop also included a prioritisation process to help the team identify the most promising analogue cases, taking into account factors such as their relevance, coverage and research team resources. The analogues were also selected to cover the whole CCS chain. The project team subsequently used the workshop outcomes to agree a final shortlist of nine analogue case studies, each of which covers a defined time period (see Table 2). The research for each case study was carried out using a combination of literature reviews and, in some cases, a few expert interviews to fill gaps in the published data and analysis.

Table 1. Uncertainties and indicators

Key uncertainty	Indicators
1. Variety of pathways The diversity of technological options represents an uncertainty because early selection might accelerate development, but risks locking in weak technologies.	- Number of technology variants - Relative importance of variants for technology developers - Market share of technology variants - Extent of lock-in / dominance of particular technology variant
2. Safe storage There is uncertainty as to whether geological storage of CO_2 will be secure over long time periods, and whether storage risks can be reliably assessed and managed.	- Availability of storage site data, including agreed robust estimates of their capacity - Nature of legal / regulatory framework to share risks / liabilities - Levels of public awareness / acceptance of risks
3. Scaling up and speed of development and deployment There is uncertainty about whether and how fast CCS technologies can be scaled up and developed to maturity.	- Unit size, capacity and efficiency - Speed of unit scaling - Cumulative investment / installed capacity - Relative importance of market niches
4. Integration of CCS systems It is unclear how CCS systems will be integrated. Integration is a technical challenge, as well as an issue of organisation and governance.	- Whether full chain integration has been achieved? - The allocation of responsibility for integration - Presence, role and importance of 'system integrator' actors - Nature of development, including roles of key actors and the relative importance of 'bottom up' / emergent and 'top down' / directed development
5. Economic and financial viability The future cost and financial risk of implementing CCS are very uncertain. The economic and financial uncertainty is heavily dependent on policy.	- Costs, including assessment of quality of cost data - Key financial risks and 'financeability' - Role of subsidies, other forms of economic / financial support, and other sources of finance (shared with uncertainty 6)
6. Policy, politics and regulation CCS development is strongly influenced by uncertainties about extent of political support, as well as the choice and design of policies and regulations.	- Nature of legal / regulatory framework to share risks / liabilities - Role of subsidies, other forms of economic / financial support, and other sources of finance (shared with uncertainty 5) - Role of other forms of policy support - Extent of political commitment / legitimacy
7. Public acceptance Public acceptance may be crucial to CCS development. Attitudes to CCS are shaped in social interaction.	- Levels of public awareness / acceptance of risks - Specific manifestation of public opposition (or support) - Quality of public engagement

Table 2. Analogue case studies

Uncertainty	Historical analogue case studies
1. Variety of pathways	The French Nuclear Programme, 1950s-1980s
2. Safe storage	The management of radioactive waste in the UK, 1956-2011
3. Scaling up and speed of development and deployment	The UK 'Dash for Gas', 1987-2000 Flue Gas Desulphurisation in the USA, 1960s-2009
4. Integration of CCS systems	Natural Gas Network in the UK, 1960-2010
5. Economic and financial viability	Flue Gas Desulphurisation in the USA, 1960s-1970s Investments in landfill in the UK, 2001-2011
6. Policy, politics and regulation	Flue Gas Desulphurisation in the UK, 1980s to 2009
7. Public acceptance	Natural gas infrastructure development in the UK, 2000-11

Each case is briefly described below. Full details can be found in case study reports which are available on the research project website[a].

3.1. Variety of pathways

This uncertainty has been analysed through a case study of the development and deployment of nuclear power in France from the 1950s-1980s. The French nuclear programme is widely seen as a successful example of a large scale, rapid roll-out of a standardised design [12]. In the 1950s, a variety of different reactor designs were available internationally [13]. The case analysed the process by which this initial variety was reduced to one dominant design. This case is a partial analogue for the possible development of CCS as there is currently technological diversity for each of the components of the CCS chain. According to insights from the innovation studies literature, competition among technology variants is normal and beneficial for learning, but will most likely be reduced as technologies get nearer wide deployment. There is uncertainty as to what technologies will win out and when that will happen. This raises questions about when to support a diversity of designs and when to prioritise specific variants.

Initially, in France, a domestic design of gas-cooled graphite reactors (GCR) was developed, but subsequently the French opted for an American pressurised water reactor (PWR) design, which also became dominant globally. Later, France also invested significant resources into the development of a fast breeder reactor (FBR), which was never commercialised. The history of the French nuclear programme illustrates that technological variety can be reduced by policy, albeit with significant risks if it is not possible to identify which variant is the 'best'. A number of technical and political rather than economic factors played a key role in the process of choosing the design for the French nuclear roll-out. Thereafter, standardisation contributed to lower costs and shorter construction times compared to other countries.

3.2. Safe storage

This uncertainty has been analysed with the help of one case study: the management of radioactive waste in the UK. Radioactive waste (RW) management is used as an analogue for the safe storage of carbon. In both cases, the indefinite disposal of waste poses long-term environmental risks. The case study focused on four aspects of RW management: site selection, operational and accident liability and public acceptance. Two previous attempts at selecting sites for the geological disposal of RW foundered, while a third attempt is ongoing. The initial approaches were almost exclusively based on expert judgement of the technical feasibility with little public input and transparency and they faced substantial public opposition. The ongoing third attempt uses an approach suggested by the Committee on Radioactive Waste Management where local communities volunteer to host the repository, and continued public engagement is seen as key in building trust in the selection process. Operational liability refers to the financial costs of RW management and decommissioning of nuclear facilities. Liability arrangements changed over time as the nuclear industry changed from public to mainly private ownership. Whereas under public ownership no particular arrangements were made, segregated, external funds have been established under private ownership to cover the long term liabilities [14]. Arrangements for liabilities for nuclear accidents in the UK differ from those of traditional 'tort liability'. Tort liability is based on fault, is unlimited and insurance is voluntary. Nuclear liability, in contrast, is strict and channelled to the operator. Liability insurance or financial security is mandatory and the overall liability of operators is capped. Safety

[a] See http://www.ukerc.ac.uk/support/tiki-index.php?page=ES_RP_SystemsCCS

perceptions have a major impact on acceptance of nuclear energy. Surveys indicate that many people feel poorly informed about RW and have little trust in government and the nuclear industry [15].

3.3. Scaling up

This uncertainty was explored with the help of two case studies: the development of combined cycle gas turbine (CCGT) power plants (between 1900 and 1980s) and their rapid deployment in the UK in the 1990s, and the development and deployment of flue gas desulphurisation technology (FGD) in power plants in the US between the 1960s and 2009. Both technologies have been substantially scaled up in terms of the size of individual units and they have also been rolled out in substantial numbers.

The analysis of the combined cycle gas turbine showed the long time frame involved in scaling up the technology to a size of relevance for the power sector. The development from the first industrial CCGT plants to a competitive power sector technology in the 1990s took about 30 years. It required long-term, sustained R&D investment by the heavy equipment manufacturers (General Electric, Westinghouse, Siemens and ABB). Sales in niche markets enabled re-investment of revenues in R&D. Technological development also profited from sustained public R&D investment in the development of jet engines. The analysis showed how a variety of factors contributed to the surge of deployment of the technology in the 1990s. The rapid roll-out is explained by changes in economic conditions (e.g. the availability of cheap gas), policy factors (e.g. the introduction of competition in the electricity sector and stronger environmental regulations) and technological developments (efficiency improvements and scaling up). Competition between the manufacturers led to downward pressure on costs.

The analysis of FGD in the US showed that the technology went through a period of relatively rapid scaling up and development in the 1970s, and has later exhibited bursts of rapid investment activity and wide roll-out. FGD systems went through a fivefold scale up over a period of 30 years. A modular approach facilitated the relatively rapid early scaling of the overall FGD plants of 2.5 times over 5 years – and even faster for some technology variants, with scrubber unit sizes increasing more slowly. Deployment was driven by a range of different policy approaches over time, including emissions performance standards, (implicit) technology mandates and sulphur emissions trading. After a stable build rate in the 1970s, a markedly uneven rate of build can be observed in the 1980s onwards, with peaks of several 10s of GWs installed in some years. At times, this caused worries about the ability of industry to scale-up its capacity quickly enough. Part of the reason why this has worked is the international nature of the FGD equipment market that has smoothed out overall demand. Towards the end of the period studied, there were however signs of FGD ‘booms’ in several markets coinciding in time, with renewed worries about industry capacity bottlenecks forming.

3.4. System integration

This uncertainty was explored with the help of a case study on the transition of the system for gas provision in the UK from town gas to natural gas, during the period from 1960 to 2010. The study was chosen as an analogue for the challenges of integrating large, infrastructural technical systems. From 1960 to the mid-1980s, the gas infrastructure was under nationalised governance with the Gas Council as the dominant actor. The introduction of liquefied natural gas (LNG) from 1964 facilitated the later conversion from town gas to natural gas, by providing a ‘back bone’ pipeline up the middle of England. The introduction of LNG created several challenges, including the higher pressure needed for natural gas, the conversion of burners in domestic appliances and the need for new expertise. The introduction of North Sea gas from the late 1960s drove a change process, in which resilience and flexibility were sought, and provided by interconnections, storage and new control technologies. The period from the mid-1980s brought privatisation and market liberalisation, and a multitude of actors contributing to the development of the system. From the late 1990s, the depletion of North Sea resources led to a renewed emphasis on gas imports – and a simultaneous rise in political debate about the security of UK gas supplies. The need to expand imports led to large scale investments in new pipeline interconnectors and LNG import terminals.

3.5. Economic and financial viability

We chose two cases to shed light on economic and financial uncertainties: the storage in landfill sites of waste in the UK from 2001 to 2011; and flue gas desulphurisation in the United States in the 1960s and 1970s. Landfilling of waste is considered as a suitable regulatory analogue to carbon storage because both activities raise questions about the long-term environmental risks and associated liabilities of dealing with waste streams. Landfilling also has a number of operational characteristics which make it similar to carbon storage (for example a long aftercare phase after operations have stopped). The EU CCS directive was directly modelled on the EU landfill directive. Whilst landfill was previously the cheapest waste management solution, it has come under intense regulatory pressure due to limits imposed by the EU landfill directive. There have been no investments in new sites since the directive was implemented in 2001. The UK government therefore introduced a number of instruments to reduce the amount of waste being sent to landfill. New void space, where necessary, has been created through an extension of existing sites. The financial provisions for monitoring and aftercare are not perceived as an important obstacle to new investments by operators. However, they do impact on operators' ability to finance projects and their balance sheets, especially when they operate multiple sites. The focus of the case was widened to include other investments in waste management infrastructure such as recycling and energy-from-waste plants. Key risks for these influencing the economic and financial viability of such investments include: off-take, waste stream, technology, policy and planning risk. It is argued that carbon storage faces similar risks.

The case study on flue gas desulphurisation (FGD) technology in the United States covers the mid-1960s to the late 1970s; the period when the technology began receiving serious attention and investment. The first large scale FGD plant was built in the late 1960s. Based on that and other evidence, regulators introduced an emissions performance standard in 1971. The government also supported the technology through funding R&D, establishing test centres and sharing data. Litigation created policy uncertainty and delayed investments, but ultimately the standard stood up against the challenges. Subsequent regulation enacted in 1979 was more stringent and effectively mandated FGD. FGD costs rose five-fold in the period studied, and they subsequently fell substantially in the 1980s. The increases were due to unforeseen technical problems and the challenges of technology transfer from other sectors. This rise in costs was much bigger than predicted at the time when the first large plant came on line. Financial risk was not a key problem for the investing utilities, since they operated in regulated, regional monopoly markets and were allowed to pass on abatement costs to their customers.

3.6. Policy, politics and regulation

This uncertainty has been explored through a case study of FGD technology deployment at power plants in the UK between the early 1980s and 2009. This analogue was selected because FGD deployment is dependent on policy and regulation, and policies to support FGD in the UK have been subject to significant uncertainty and controversy. During the 1980s international concerns about acid rain began to drive policy discussions about sulphur emissions abatement in the UK. The EU adopted the Large Combustion Plant Directive (LCPD) in 1988 which included limits on these emissions. The LCPD has had significant impacts on FGD investment in the UK, but this has also been a politicised process. Whilst the EU promoted emissions reductions and the use of FGD, the UK government and industry resisted abatement investments that were considered too costly. Therefore, FGD investments were made but were delayed. More recent EU regulations which mandate closure of unabated fossil fuel plants by 2015, together with financial incentives under the second phase of the EU Emissions Trading Scheme, have stimulated a rapid increase in investment. By 2008, power sector SO_2 emissions had been reduced by 94% compared to 1980 levels as a result of fuel switching (from coal to gas), the use of lower sulphur coals, and the introduction of FGD. The overall UK FGD investment programme cost £1.4-1.8bn in 2011 prices.

3.7. Public acceptance

This uncertainty was explored with the help of a case study on the public acceptance of the development of natural gas infrastructures in the UK between 2000 and 2011. This case was selected because natural gas infrastructure development is similar to the transport infrastructure needed for CCS, particularly pipelines and compressor stations. The study includes the use of salt and brine fields for underground gas storage (UGS), the development of Liquefied Natural Gas (LNG) terminals with above-ground storage tanks and the construction of pipelines (and pressure reduction installations) to connect new facilities with the national gas transmission system. The case is also relevant because recent investments in onshore gas pipeline and storage infrastructure in the UK have been accompanied by local protests and opposition, with some material impacts on project outcomes.

4. CCS pathways to 2030

A set of pathways was developed for CCS from now to 2030, drawing on CCS policy documents, research literature and the insights gained from the analogue case studies. The pathways were analysed with the help of the uncertainty indicators listed in Table 1. For each uncertainty and assessment indicator, the pathways were compared at five-year intervals to see where they differ. These differences were identified as branching points between pathways [16].

A set of three pathway end-points for 2030 were selected, which differ widely in the amount of CCS deployed. These endpoints represent situations where we have either (1) reached the more ambitious policy targets for CCS deployment (and where virtuous cycles have led to the resolution of many uncertainties; (2) a situation where a moderate level of deployment has emerged and the success of the technology 'hangs in the balance'; or (3) CCS has failed to 'deliver' completely (and where vicious cycles have led to a multiplication of uncertainties).

To be able to elaborate the possible events leading to each of these endpoints, a back-casting approach was adopted [17]. During the course of this back-casting analysis, the second pathway was expanded into two variants in order to illustrate the trade off involved in early or late selection of technology variants (and a number of other closely related issues). The pathways are deliberately agnostic with regard to CCS plant fuel and technology choices because the main aim was to focus on the insights from the case studies. Full descriptions of each pathway, including the wider energy system and policy context for each, can be found in Heptonstall, Markusson et al. [18]. The pathways are:

- Pathway 1: 'On track' is a broadly successful pathway, with a plausibly high level of CCS deployment. By 2030, CCS has an established position as a technically proven and financially viable option, and is competitive with other low-carbon electricity generation technologies.
- Pathway 2, Variant A: 'Momentum lost'. Commercial-scale demonstration of CCS goes ahead, and is followed quickly by further deployment up to the mid-2020s. By this time, CCS has established itself as technically viable, but from the mid-2020s onwards it is not generally a preferred option as part of the low-carbon generation mix in the UK. Financial viability ends up being marginal.

- Pathway 2, Variant B: 'Slow and sporadic'. Commercial-scale demonstration of CCS does go ahead, followed by limited further deployment up to 2030. CCS has established itself as technically viable, but it is not generally a preferred option as part of the low-carbon generation mix in the UK. Financial viability remains marginal with deployment in particular market niches only.
- Pathway 3: 'Failure' No CCS deployment beyond a limited demonstration programme.

The deployment of CCS plants within each pathway is summarized in Figure 1 together with the four key branching points. The branching points are explained in more detail in Figure 2.

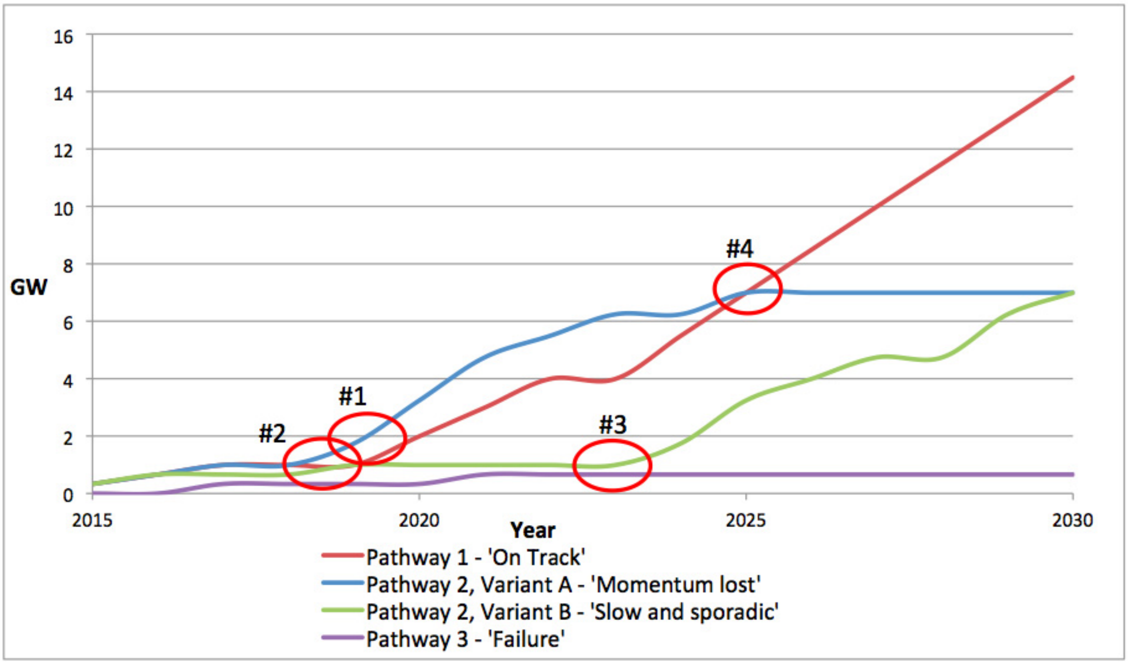

Fig. 1. Pathways for CCS in the UK to 2030

Branching Point #1 represents a choice between strong, comprehensive early policy support or a more limited and partial approach. Branching Point #2 is where a 'Failure' pathway branches off, either as a result of political will being too weak, or through the emergence of a 'show stopper issue' of a technical or social kind. In between these two branching points, there is the 'Slow and sporadic' pathway with a moderate level of policy support and moderately successful development work, which – with a combination of luck and prudent planning – could lead to a deployment in specific market niches the late 2020s. Branching Point #3 illustrates that there is a need for sustained progress to avoid the pathway grinding to a halt in the 2020s. Leftmost in Figure 2 is the 'On track' pathway where CCS develops the strongest momentum, through all the uncertainties improving. The final branching point, Branching Point #4, suggests that if early progress is achieved through cutting of too many corners and premature selection of technology variants, there is a risk of a backlash in the (late) 2020s and momentum being lost.

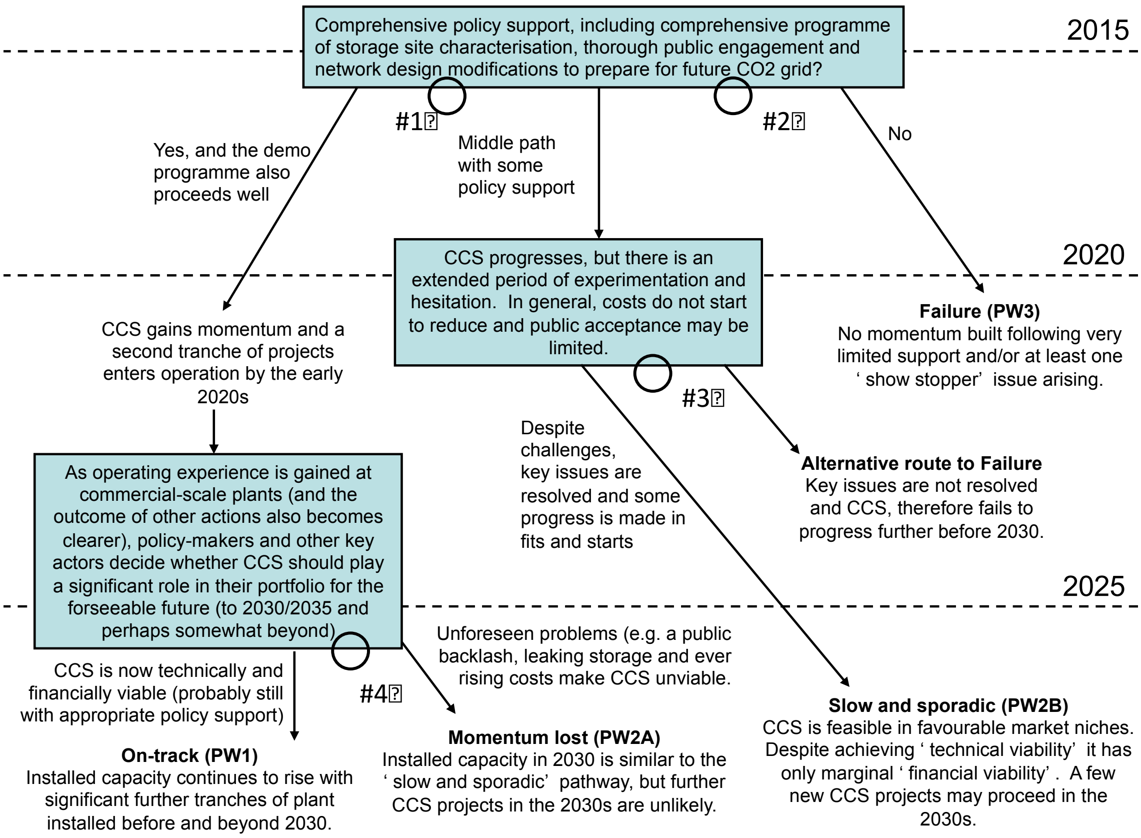

Fig. 2. Pathways for CCS in the UK to 2030 with branching points

5. Conclusions and policy implications

CCS technologies continue to face multiple uncertainties. Recent events in the UK and abroad reinforce the need to analyse these uncertainties, and possible ways in which they could be overcome. The UK government has continued its commitment to CCS, and has re-launched its demonstration programme. But at the time of writing, this has not yet resulted in a firm agreement to fund a specific demonstration project. The cancellation of Longannet has shown some of the challenges of securing financing for large-scale CCS projects [19]. The spotlight has now shifted to other CCS projects that are bidding for support within the new CCS commercialisation programme. Despite continuing public commitments to CCS from the government, and the publication of the CCS roadmap, policy uncertainties are likely to remain a particular concern for investors.

In view of these persistent uncertainties and the slow progress with demonstration projects, what insights can our research offer for policy and other decision makers? There are some important general lessons. First, our historical case studies show that uncertainties can be reduced sufficiently for progress to be made. In some cases, they can be resolved entirely. This offers some optimism that, given the right set of circumstances, the uncertainties that affect CCS can also be dealt with over time. However, we have also emphasised that care is needed when learning from historical contexts that differ widely from the current situation in the UK. It is important to consider the limitations revealed by the analogues in relation to CCS, as well as the lessons they can teach us.

A second general conclusion is that interactions between uncertainties matter. They can reinforce each other, both positively and negatively. There can also be trade-offs between uncertainties where attempts to resolve one uncertainty could result in the exacerbation of others. This reinforces the need for a systemic analysis of emerging technologies such as CCS, to complement more specific research on particular technical, economic, policy and social issues. In section 4 of this paper, we have highlighted how particular trade-offs between uncertainties can make a significant difference to outcomes for CCS. The variants of pathway 2 explore some of the risks of a strong policy that pushes technology development down a specific route – and how this strategy may lead to a backlash, and an eventual stalling of progress.

A third lesson is that the resolution of all uncertainties is not required for CCS to be financeable in the UK. Similarly, the derailing of plans to realise the potential of CCS may not require everything to go wrong – but this could be caused by a 'critical mass' of uncertainties persisting for too long. With respect to emerging technologies like CCS, it is tempting to feel that all risks must be dealt with by government before progress can be made. But that assumption is mistaken, and forgets that the private sector routinely deals with multiple risks. If new low-carbon technologies such as CCS are to be deployed, the role of policy frameworks is not to remove all uncertainties, but to identify those risks that would not be tackled in the absence of intervention.

Whilst the 'on track' pathway discussed in -this paper describes how many of the uncertainties facing CCS could be resolved -, we have stressed that it is not meant to be prescriptive. The reality of support for CCS in the UK is likely to be much less straightforward. Our analysis has highlighted difficult choices that have to be made by government and other decision makers, especially in the following four areas:

1. <u>Keeping options open or closing them down</u>? Whilst strong policy signals and support are required for CCS, there are also risks associated with accelerated innovation and deployment. It is tempting to focus resources on one technological variety early on as the French government did with the PWR for its nuclear programme. This may help to speed up development, but comes with increased risks of picking inferior technology. It is too early for government and industry to close down on a particular variant of CCS technology. Several substantial demonstration projects are needed, for example so that uncertainties associated with scaling up and system integration can be tackled.

2. <u>Which public policy incentives for CCS demonstration and deployment</u>? A menu of options is available for public policy support of CCS technologies. A regulatory approach will only work if technologies are sufficiently well developed and the additional costs can be passed on to consumers. CCS technologies are not yet at this stage. In the meantime, the government is right to emphasise the need for demonstrations. Public finance for these demonstrations should be designed to maximise performance rather than novelty. Since not all demonstrations are likely to perform as expected, systematic learning and evaluation by government is also essential.

3. <u>CCS deployment as a marathon, not a sprint</u>. Our historical case studies show that developing new energy technologies can take a long time. Their costs do not necessarily fall from the first day they are deployed. Whilst learning can bring costs down, costs can rise for several years first as technologies are scaled up. Whilst this requires some patience, it is therefore important to monitor progress carefully to inform decisions on whether to continue with public funding – or, if there is little sign of positive progress over a prolonged period of time, when to divert resources to other options.

4. <u>Dealing with storage liabilities</u>. Our case study of UK nuclear waste management policy has highlighted how complex liability arrangements for CO2 storage could be. For CCS, a balance needs to be struck between limiting liabilities for investors (so that they will be able to invest in full scale CCS plants) and protecting the interests of future taxpayers (who should not be un-necessarily exposed to liabilities). Agreements are therefore needed about how liabilities should be divided, when a privately run storage site

should revert back to the State, what arrangements are needed to fund potential liabilities, and what insurance site operators may require. The nuclear experience suggests that an independently managed fund may be required for carbon storage liabilities.

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